

# Intelligent Gradient Detection on MPPT Control for Variable Speed Wind Energy Conversion System

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**Abstract**—The problem of control associated wind energy conversion systems using horizontal-axis fixed-pitch variable speed low-power, working in the partial load region, consisting in the energy conversion maximization, is approached here under the assumption that the wind turbine model and its parameters are poorly known. Intelligent gradient detection method by using Maximum Power Point Tracking (MPPT) fuzzy control approach is proposed control solution aims at driving the average position of the operating point near to optimality. The reference of turbine rotor speed is adjusted such that the turbine operates around maximum power for the current wind speed value. In order to establish whether this reference must be either increased or decreased, it is necessary to estimate the current position of the operating point in relation to the maximum power-rotor speed curve characteristic by many fuzzy rules. Numerical simulations are used for preliminary checking performance of the MPPT control law based on this intelligent gradient detection.

**Index Terms**—MPPT, wind energy, optimal control, WECS

## I. INTRODUCTION

The worldwide concern about the environmental pollution and the possible energy shortage has led to increasing interest in technologies for generation of renewable electrical energy. Among various renewable energy sources, wind generation has been the leading source in the power industry. In order to meet power needs, taking into account economical and environmental factors, wind energy conversion is gradually gaining interest as a suitable source of renewable energy [1]. The wind energy conversion system (WECS) control field vary in accordance with some assumptions concerning the known models or parameters, the measurable variables, the control method employed, and the version of WECS model used. The power that developed by a wind turbine depends not only on the air velocity but also on the speed of the turbine. The speed at which maximum power is developed a function of wind velocity. In order to extract maximum power, the speed of the turbine has to be controlled as a function of wind velocity. Control of WECS in the partial load regime generally aims at regulating the power harvested from wind by modifying the electrical generator speed; in particular, the control goal can be to capture the maximum power available from the wind. For each wind speed, there is a certain rotational speed at which the power curve of a given wind turbine has a maximum (reaches its maximum value) [2]. Many researchers have proposed different control schemes in WECS. Some controller designs employ anemometers to measure wind velocity [3]. These mechanical sensors increase the cost and reduce the reliability of the overall system. The

measurements can be seriously perturbed by turbulence. Due to the difficulties in wind speed measurement, a control strategy based on the tip-speed ratio is practically difficult to implement. Consequently methods of wind speed estimation have been suggested [4-6], the approach employs the hill-climbing method for dynamically driving the operating point, by using some searching signal in order to obtain gradient estimations of some measurable variables. Based on the operating point position on the power characteristic, the rotational speed is controlled in the sense of approaching the maximum power available. In this paper the improvement optimal control of variable-speed fixed-pitch WECS based upon maximum power point tracking (MPPT) will be discussed, when the tips speed and power coefficient parameters are not known. Intelligent gradient detection on MPPT uses the generator speed and active power output measurements to search for the optimum speed at which the turbine should operate for producing maximum power. MPPT controller will generate a rotor speed reference based on the result of intelligent gradient detection system. Performances of classical MPPT control and MPPT fuzzy control based on intelligent gradient detection will be compared. Effectiveness of the proposed control scheme will be validated through computer simulations under varying wind speeds.

## II. WIND ENERGY CONVERSION SYSTEMS

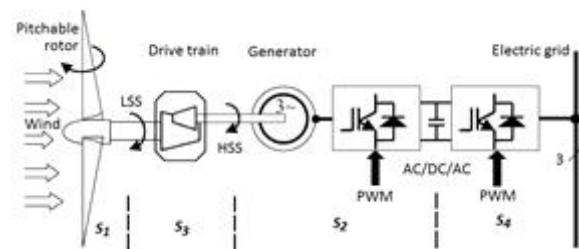


Figure 1. Wind energy conversion systems.

Fig. 1 presents wind power conversion systems, which uses squirrel-cage induction generator (SCIG). From the system viewpoint, the conversion chain can be divided into four interacting main components which will be separately modeled: the aerodynamic subsystem **S1** and the electromagnetic subsystem **S2** interact by means of the drive train mechanical transmission **S3**, whereas **S4** denotes the grid interface.

### A. Wind Turbine Characteristics

Fig. 2 shows a variable speed wind turbines have three

main regions of operation[7]. A stopped turbine is just starting up is considered to be operating in region 1. Region 2 is an operational mode with the objective of maximizing wind energy capture by using control strategies such as yaw drive, generator torque, and blade pitch. In region 3, which occurs above rated wind speed, the turbine must limit the captured wind power so that safe electrical and mechanical loads are not exceeded. For the variable-speed wind turbines operating in region 2, the primary objective is to maximize energy capture. The power extracted from a wind turbine is a function the wind power available, the power curve of the machine, and the skill of the machine to react to wind variations. The power and torque extracted from the wind in region 2 can be expressed as

$$P_{wt} = \frac{1}{2} \rho C_p(\lambda) \pi R^2 v^3 \quad (1)$$

$$\Gamma_{wt} = \frac{P_{wt}}{\Omega_i} = \frac{1}{2} \rho C_T(\lambda) \pi R^3 v^2 \quad (2)$$

where  $P_{wt}$  is the rotor mechanical power (W),  $\Gamma_{wt}$  is the turbine torque (Nm),  $v$  is the wind speed at the center of the rotor (m/s),  $R$  is the turbine radius (m),  $\rho$  is the air density (kg/m<sup>3</sup>),  $\Omega_i = \lambda v / R$  is the rotor angular velocity (rad/sec),  $C_p$  is the rotor power coefficient, the percentage of the kinetic energy of the incident air mass that is converted to mechanical energy by the rotor,  $C_T$  is the torque coefficient. Both values of  $C_p$  and  $C_T$  are nonlinear functions with respect to the tip speed ratio and the pitch angle and have the following relation  $C_p(\lambda) = \lambda C_T(\lambda)$ ,  $\lambda$  is the tip speed ratio, the ratio between blade tip speed and wind speed upstream the rotor. An example of power coefficient versus tip speed ratio curve is shown in Fig. 3. Clearly the turbine speed should be changed with wind speed so that optimum tip speed ratio  $\lambda_{opt}$  is maintained. The following equation provides the expression of the maximum aerodynamic torque of the wind turbine when the pitch angle value's is fixed, so the relation of the turbine power with turbine rotor speed and wind speed is non-linear:

$$P_{maxpt} = \frac{\rho C_{p,max}(\lambda_{opt}) \pi R^2 \Omega_i^3}{2 \lambda_{opt}^3} \quad (3)$$

### B. Generator Model

The electrical generators are systems whose power regime is generally controlled by means of power electronics converters. From this viewpoint, irrespective of their particular topologies, controlled electrical generators are systems whose inputs are stator and rotor voltages, having as state variables the stator and rotor currents or fluxes[2]. They are composed of an electromagnetic subsystem and the electromechanical subsystem, through which the generator experiences a mechanical interaction. Fig. 4 illustrates the modeling principle for the SCIG. The necessity of using  $(d,q)$  models comes from vector control implementation, which has the advantage of ensuring torque variation minimization and thus better motion control.

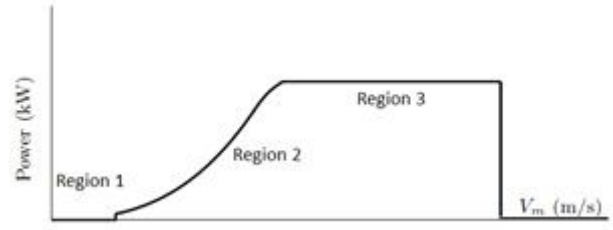


Figure 2. Power curve of wind turbine.

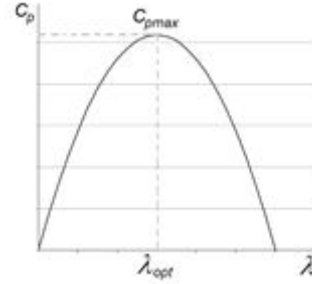


Figure 3. Power curve expressing the aerodynamic efficiency.

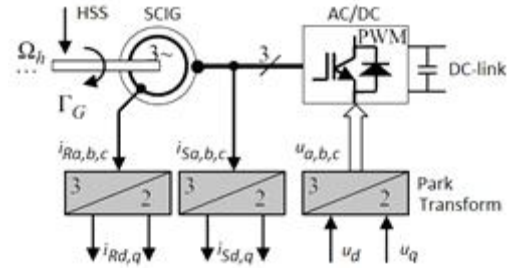


Figure 4. Electromagnetic and electromechanical of SCIG.

Many set equations involving the generator's electrical variables-voltages, fluxes and currents-results. In wind energy conversion systems, the generator interacts with the drive train; hence, to this set of equations is usually added the high-speed shaft (HSS) motion equation in the form

$$J \frac{d\Omega_h}{dt} = \Gamma_{mec} - \Gamma_g \quad (4)$$

where the static and viscous frictions have been neglected,  $J$  is the equivalent inertia rendered to the HSS,  $\Gamma_{mec}$  is the mechanical torque,  $\Omega_h$  is the HSS rotational speed and  $\Gamma_g$  is the electromagnetic torque resulting from the interaction between the stator and rotor fluxes. The modeling has assumed that the influence of the generator constructive features on its dynamics is neglected and its parameters are constant. The SCIG electromagnetic torque is expressed in  $(d,q)$  frame as:

$$\Gamma_g = 3/2 p L_m (i_{sq} i_{rd} - i_{rd} i_{sq}) \quad (5)$$

with  $p$  being the pole pairs number,  $L_m$  the stator-rotor mutual inductance,  $i_{sd}$ ,  $i_{sq}$ ,  $i_{rd}$  and  $i_{rq}$  are the stator, respectively rotor current  $(d,q)$  components. The SCIG model can be obtained by setting the  $d$  and  $q$  components of the rotor voltage to zero[9].

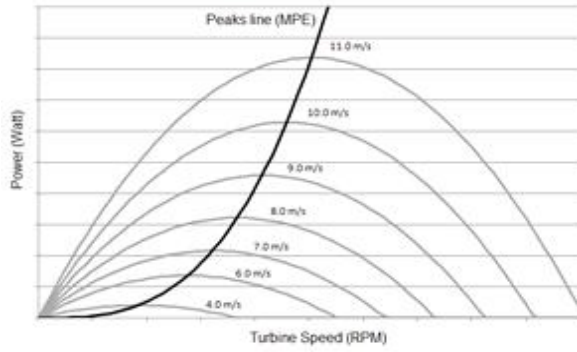


Figure 5. Power rotor speed with wind speed as parameter.

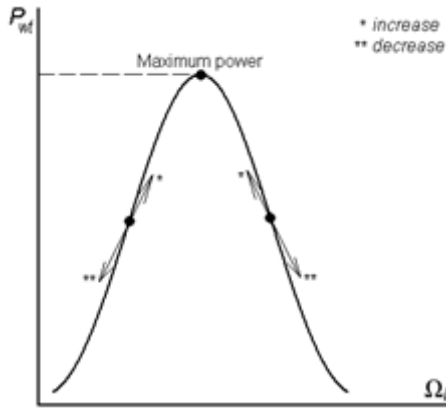


Figure 6. Decision cases for MPPT control on the static power curve.

TABLE I  
REFERENCE OF TURBINE

$\partial\Omega_r/\partial t$	$\partial P_w/\partial t$	
	$< 0$	$> 0$
$< 0$	$\Omega_r$ increase	$\Omega_r$ decrease
$> 0$	$\Omega_r$ decrease	$\Omega_r$ increase

### III. PROPOSED MPPT CONTROL APPROACH

#### A. MPPT Based On Turbine Power Characteristic

Control of variable-speed fixed-pitch WECS in the partial load (region 2 in Fig. 2) generally aims at regulating the power harvested from wind by modifying the electrical generator speed; in particular, the control goal can be to capture the maximum power available from the wind. For each wind speed, there is a certain rotational speed at which the power curve of a given wind turbine has a maximum ( $C_p$  reaches its maximum value). Fig. 5 shows about compose all these maximum value is known as the maximum power efficiency (MPE)[8]. By keeping the static operating point of the turbine around the MPE one ensures an optimal steady-state regime, that is the captured power is the maximal one available from the wind. The reference of the rotational speed control loop is adjusted such that the turbine operates around maximum power for the current wind speed value. In order to decides whether this reference must be either increased or decreased, the current position of the operating point in relation to the maximum of  $P_w(\Omega_r)$  curve must be estimated. Fig. 6 illustrates about the variable speed control system is used in MPPT optimal control. The approach is based on the gradient

computation of the power  $P_w$  and rotational speed  $\Omega_r$  employed in a hill-climbing-like method. To determine  $\partial P_w / \partial \Omega_r$  value, the result of computation of the power and rotational speed gradients is used, its sign corresponding to the position of the static operating point on the power curve in relation to the maximum of this curve. Given that the WECS parameters ( $\lambda_{opt}$  and  $C_{pmax}$ ) are unknown, the MPPT algorithms generally aim at maintaining the optimal operating point by zeroing value of  $\partial P_w / \partial \Omega_r$ . Therefore, the wind turbine speed reference, depends on the operating point position and on its moving trend, expressed by the sign of  $\partial P_w / \partial \Omega_r$  (see Table I and Fig. 6).

#### B. Fuzzy Logic Based Gradient Detection on MPPT

Generally, variable-speed wind turbines are operated in such a way that for a power production below the rated power, in order to capture the maximum amount of energy available in the wind, the turbine operates at variable rotor speeds while the blade pitch angle is kept at a constant value[9]. Intelligent gradient detection on MPPT control startegy using fuzzy logic rules is proposed with the aim of maximizing the harvested power from the wind. Specifically, the MPPT fuzzy controller has two inputs and one output: the measured active power  $P$  generated by the generator and rotor speed  $\Omega_r$  are the inputs, while the output is the estimated maximum power that can be generated. Therefore, the fuzzy system, by acquiring and processing at each sample instant the inputs, is able to calculate the maximum power that may be generated by the wind generator by detecting a gradient of  $\partial P / \partial \Omega_r$ . The rules base is therefore built for keeping the operating point around the optimal one at a small value of  $\partial P_w / \partial \Omega_r$ . Many blocks is used to make simulation of variable speed WECS using MPPT fuzzy control variable speed WECS based on intelligent gradient detection is shown in Fig. 7. It is assumed that the turbine blades have a fixed pitch angle, so that the power output  $P$  varies non-linearly with the turbine angular speed  $\Omega_r$  and the wind speed  $v$ , as shown in Fig. 5. Hence maximum power is extracted at a particular angular speed, for a given wind speed. A vector control scheme is used to regulate the generator speed to the optimum value at which maximum power is obtained. MPPT fuzzy controller generates the optimum speed  $\Omega_r^*$  command, which is used to regulate the input current of the AC-DC converter. The output of the converter is inverted back to a constant frequency, constant voltage to supply AC loads. The controller applies small changes in the speed command at regular intervals, and monitors the corresponding changes in the actual speed  $\Delta\Omega_r$  and generator output power  $\Delta P$ , respectively. The controller does not require measurement of the wind speed to search for the optimum operating point. The inputs to the MPPT fuzzy controller at the  $k_{th}$  sampling instant are respectively given by

$$\Delta P(k) = G_p (P(k) - P(k-1)) \quad (6)$$

and

$$\Delta \Omega_r(k) = G_\Omega (\Omega_r(k) - \Omega_r(k-1)) \quad (7)$$

where  $G_p$  and  $G_\Omega$  are the input scaling gains to the controller. These input gains, along with the output gain  $G_o$ , are tuned so that the speed command eventually converges to the

required value for maximum power output.

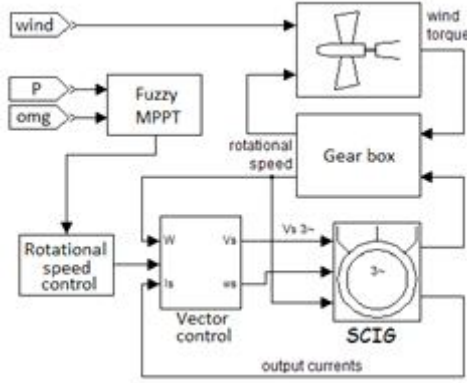


Figure 7. Simulation of WECS.

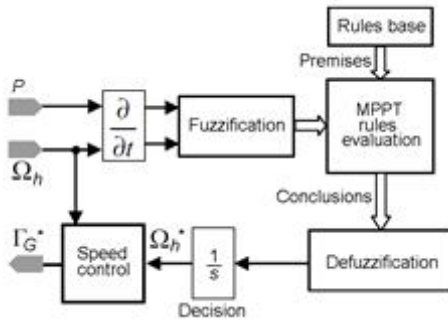


Figure 8. MPPT fuzzy control block.

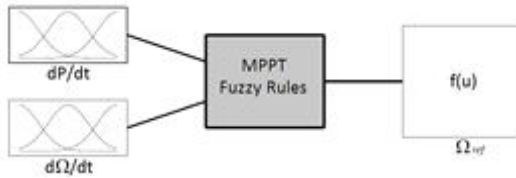


Figure 9. Fuzzy rules based MPPT control.

Two membership functions are used to describe each of the input and output variables of the controller. Triangular membership functions used throughout, except for the outer membership functions of  $\Delta\Omega_h(k)$  and  $\Delta P(k)$ , which saturate at  $\pm 1$ . The controller real-valued input variables are fuzzified by mapping onto the input membership functions. Each linguistic variable can take a numeric linguistic value -1 to +1, representing real values ranging from negative to positive. The MPPT fuzzy block as shown in Fig. 9 consists 4 rules :

**IF  $\partial P/\partial t < 0$  and  $\partial \Omega/\partial t < 0$  THEN  $\Omega_{ref}$  = increase**  
**IF  $\partial P/\partial t < 0$  and  $\partial \Omega/\partial t > 0$  THEN  $\Omega_{ref}$  = decrease**  
**IF  $\partial P/\partial t > 0$  and  $\partial \Omega/\partial t < 0$  THEN  $\Omega_{ref}$  = decrease**  
**IF  $\partial P/\partial t > 0$  and  $\partial \Omega/\partial t > 0$  THEN  $\Omega_{ref}$  = increase**

The product operator is used for premise quantification and determination of the implied fuzzy set for each rule that is active. In the defuzzification stage, the Sugeno method is used on the implied fuzzy sets to generate a crisp output, corresponding to the change in speed command  $\Omega_h^*$ . The speed reference signal is computed as:

$$\Omega_h^*(k) = G_s(T\Delta\Omega_h^*(k) - \Omega_h^*(k-1)) \quad (8)$$

where  $T$  is the sampling time period.

#### IV. DISCUSSION OF SIMULATION RESULTS

A low-power variable-speed fixed-pitch WECS has been used here as case study. This WECS has been subjected to both classical MPPT control and MPPT fuzzy control. The classical MPPT control based on Boolean logic, meanwhile MPPT fuzzy control based on intelligent gradient detection approach. Below some simulation results are discussed comparatively. Both sets of simulations have been done for 1000 second a wind sequence having the average speed of about 8 m/s and a medium turbulence intensity as show in Fig. 10, obtained using the von Karman spectrum in the IEC standard. A 6kW SCIG based WECS model is used as a case study for simulating the proposed approach performance. The WECS model is built by using  $\rho = 1.25\text{kg/m}^3$ ,  $R = 2.5\text{m}$ ,  $\lambda_{opt} = 7$ , and  $C_{pmax} = 0.47$ . Fig. 11 presents the evolution of power coefficient  $C_p$  values in the same time interval of wind. It is showing the  $C_p$  values of MPPT fuzzy close to the optimal one appear the most often than classical MPPT method, so the performance of MPPT fuzzy is better than classical MPPT. The variation of  $C_p$  for both MPPT control method is depended on the current wind speed and it will close to the maximum value when the operation of wind speed are around 6-8 m/s, that is range of the wind speed for the partial loading area as mentions in the Fig. 2 that will be maximizing power energy capture from wind by MPPT control approach. When the wind speed is sudently drop, also the value of  $C_p$  in the both MPPT control approach are sudently decrease. The performance of the simulation results can be improved than MPPT classical method by applying MPPT fuzzy control approach based on the intelligent gradient detection algorithm. The fuzzy rules will detect change of turbine power and the rotor speed each time to decide the optimal rotor speed reference for the next time step. The turbine has variable speed capability, being equipped with a speed controller based on a vector control structure. The tests concern only the partial load region for medium wind turbulence. For the wind speed more than 8 m/s, the characteristic of wind turbine belong in the rate power region, so the control for it will using mechanical control approach by change a pitch angle in the blade. Fig. 12 compares the variation of the genarotor rotor speed between MPPT fuzzy and classical MPPT during 1000 second wind speed simulation. Similar with the  $C_p$  characteristics in the Fig. 11, also MPPT fuzzy method can improves the performance of generator rotor speed than classical MPPT method. Both of MPPT control approach are capable follows the variation of wind speed. A mechanical power change from the variation of wind speed will be compensated by changes the generator rotor speed reference that is produced by MPPT block control to achieve optimal generation of power. When the  $C_p$  close with optimal value one, the rotor speed of generator similar with wind speed behavoiurs's because the linear correlation caractereistic between them, it is presented during simulation for 500 until 700 second that is the most of  $C_p$  close optimal condition value.

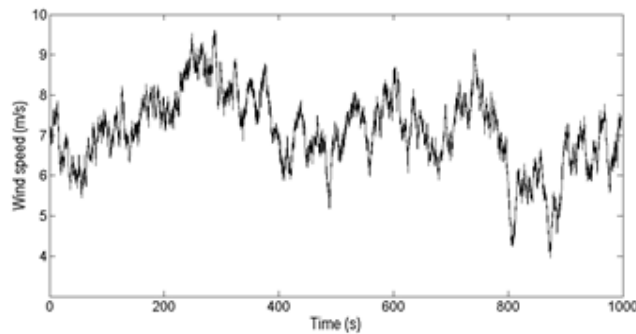


Figure 10. Wind speed sequence used for assessing the MPPT control.

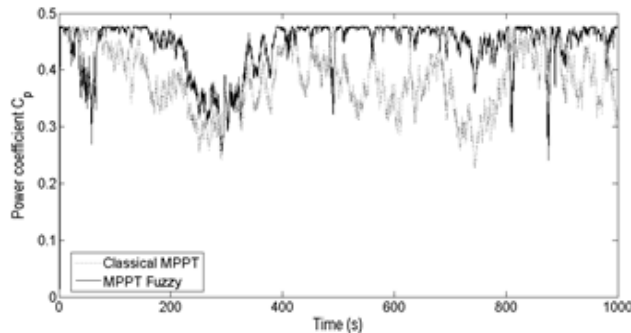


Figure 11. Evolution of the power coefficient.

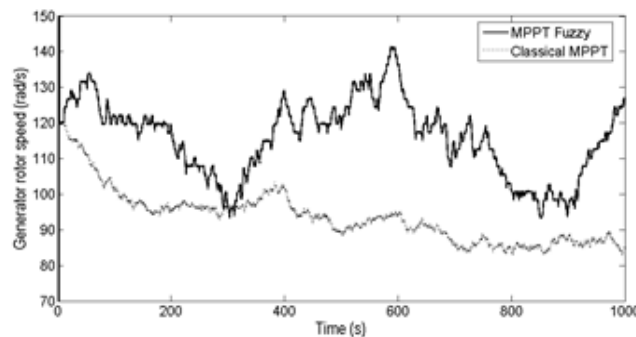


Figure 12. Evolution of the generator rotor speed.

Fig. 13 shows about turbine power and operation range of variation rotor speed of wind turbine characteristic. The MPE curve can be used to know about the effectiveness and performances of WECS control approach for both classical MPPT and MPPT fuzzy control approach to find out the optimal power. The turbine power and the operation range of turbine rotor become more wide than classical MPPT by applying intelligent gradient detection on MPPT fuzzy control. Also the turbine rotor speed characteristic of MPPT fuzzy control more close to the MPE curve.

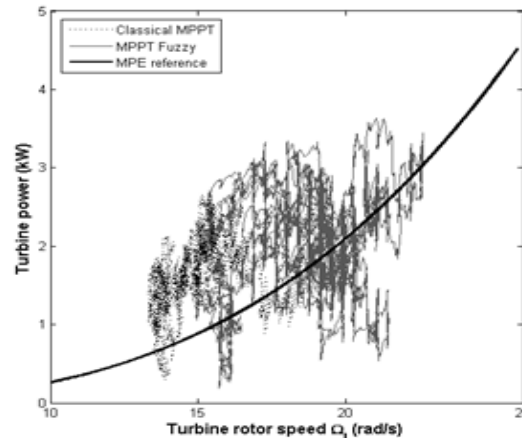


Figure 13. Power wind turbine and range of rotor speed characteristic.

## V. CONCLUSION

MPPT fuzzy control based on intelligent gradient detection for extracting maximum power from a variable speed wind turbine has been presented. It has been shown that the turbine power output depends nonlinearly on its angular rotor speed and the wind speed. MPPT fuzzy control approach is well suited for searching the optimum speed at which the turbine should operate under varying wind conditions. The performance of the proposed scheme has been simulated under changes in wind. It has been shown that the fuzzy controller adjusts the angular rotor speed so that the turbine power coefficient close/converges to its maximum value in the steady state.

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